THE EFFECTS OF DESIGN PARAMETERS AND OPERATING CONDITIONS ON THE CREEP LIFE OF HIGH PRESSURE TURBINE (HPT) BLADE-INDUSTRIAL GAS TURBINE ENGINE

Wanis A.E.M Elatod[1], Abdo-Almonaim S.M. Alghlam[2*], and Tarak Assaleh[3]

[1] University of Zawia, Faculty of Engineering/Department of Mech. Eng., Zawia-Libya
[2,3] University of Sabratha, Faculty of Engineering/Department of Mech. Eng., Sabratha-Libya
[*] utmabdo73@gmail.com

Abstract

Peak load operation requires gas turbines to operate at high firing temperature, which consequently reduces the useful lives of components. This paper studies the quantitative relationship between gas turbine power setting and the hot gas-path components' life consumption. To achieve this purpose, a 165MW gas turbine engine was modelled and investigated in this study. A comparative lifing model, which performs stress and thermal analyses, estimates the minimum creep life of components using the parametric Larson Miller method. This lifing model was integrated with in-house performance simulation software to simulate the engine performances at design point and off-design conditions. The results showed that the combined effect of the operating environment and power demand could have significant impact on blade creep life. Predicting this impact will aid gas turbine users in the decision-making processes associated with gas turbine operation.

Keywords: Creep Life; Gas Turbine; Physics-Based Model; High-Pressure Turbine (HPT) Blade.

Introduction

The significant increase in the demand for electricity has led to a continuous improvement in the technology of industrial gas turbine engines. In addition, there is sustained need to improve efficiency, which has led to a situation where gas turbine hot section components are exposed to incredible amounts of stress and extreme temperatures. Thus, the components of gas turbine engine become subject to several failure mechanisms such as low cycle fatigue, high cycle fatigue, and thermal fatigue and creep (Weber et al., 2005).

In the case of stationary gas turbine engines, creep is a major failure mechanism that reduces hot section component life. The behaviour of creep failure mechanisms depends on engine's operating conditions, operation mode, design parameters (e.g. cooling effectiveness, material, geometry, etc) and critical hot section components, in question, details of the. Apart from the aerodynamic/thermodynamic characteristics, structural/mechanical characteristics also affect the design parameters of such components. For economic and safety reasons, life assessment is an important issue to gas turbine users. Overestimating life span of the blade can lead to failures and economic losses; on the other hand underestimating its lifespan will result in over-maintenance. Life limits provided by the original equipment manufacturer (OEM) are normally calculated on basis of a design envelope of the expected base load, calculated mechanical and thermal stresses as a function of the operating condition and the capability of the materials within those conditions. However, the guidelines do not always address the specific operating environment and requirements of each operator. In view of this, having knowledge of how an engine responds to changes in the operating and health conditions will be necessary as they affect engine performance parameters and hence alter the creep life (Abdul Ghafir et al., 2010). Time to failure can be calculated by using a lifing module based on stress and temperature variations and by using the Larson-Miller Parameter (LMP).

Several researchers have stressed the effect of design parameter and engine performance on turbine blade creep life. Eshati, S. et al. (2011) investigated the relationship between operating conditions and design parameters on the creep life of the stationary gas turbine- high pressure turbine (HPT) blade using a physics–based model [1]. A numerical approach for life assessment of the super alloy turbine blade was proposed; this approach is based on Lemaitre-Chaboche’s creep damage model (Liu, et al., 2014). Material damage is introduced into each element based on the ANSYS APDL function, and the creep damage effect is considered through the modification of Young’s modulus [2]. Mohammad and Masoud (2009) used calculative and experimental methods to predict the remaining life of an IN738 LC gas turbine blade. They used the LMP method to predict the remaining life and the effects of creep on the material microstructure was considered from metallographic, creep and hardness tests.

Using service-exposed turbine blades, Azman, M., et al. (2016) determined the remaining useful life of gas turbine blades. They used Stress Rupture Test (SRT) to perform this task under accelerated test conditions; the applied stresses to the specimen were between 400-600 MPa and 850°C. Their study focused on the creep behavior of the 52000 hours service-exposed blades, their work was enhanced with creep-rupture modelling using JM at Pro software, the work was also included the microstructure examination using optical microscope. The constitutive equations for predicting and analysing the creep deformation and creep lifetime of the blade were developed by Shi and et.al. (2015). In their research, they numerically predicted creep deformation and lifetime of an HPT blade made of a nickel-based directionally solidified (DS) superalloy. The θ-projection method was used to characterize the creep deformation of DZ125 under different temperatures and stress levels. Abdul Ghafir et al. (2010) investigated the effect of engine performance altitude and Mach number on the creep life of a high pressure turbine blade in turbo shaft engine using LMP. Other investigators focused on the interaction of different failure mechanisms with the creep. Barat and et al. (2018), Fournier and et al. (2008) addressed the interaction of creep, fatigue and oxidation. However, very limited information is available in the literature that considers the effect of power demand and other working condition on the creep life of hot section components in industrial gas turbines.

This paper studies the effect of power changes in demand at different operating conditions on the creep life consumption of the hot section components for both healthy and degraded engines. A 165MW power plant is being investigated for General Electricity Company of Libya (GECOL). The purpose of the present paper is to quantify the dependence of decreasing operational effectiveness of a gas turbine power plant upon the engines' deterioration for different operating and ambient conditions. Predicting this impact will facilitate users taking appropriate corrective actions or making changes in the mission profile and/or configuration of the engines. An in-house gas turbine performance modelling tool called Turbomatch was used by (Palmer, 1999) (Vassilios, Turbomatch Manual) to develop and simulate representative thermodynamic models of the investigated 2engine. Data collected from the Turbomatch simulations were used as input to the lifing module. Blade geometry based on a constant cross section area, stress model and its thermal properties was considered by the lifing module and the LMP to estimate the lowest blade creep life.

Life Approaches

Methods for life estimation as classified by (Eshati et al., 2010), are summarised and presented in Table (1).

Table (1): Lifing Approaches.

	Design Approach	**Post-service Approach**	**Statistical Approach**
Methods	▪ Analytical method. ▪ Empirical method. ▪ Numerical method.	▪ Non-destructive test. ▪ Destructive test.	▪ Statistical tools. ▪ Probabilistic tools. ▪ Artificial intelligent methods.
Advantages	▪ Life estimation can be performed at design stage. ▪ Low cost if low fidelity model is used.	▪ Identifies the components that need to be monitored. ▪ Offers different techniques for both destructive and non-destructive test.	▪ Reduced complexity. ▪ Fast computing. ▪ Identifies driving factors. ▪ Tackle the uncertainties
Disadvantages	▪ Based on empiric data to build the model. ▪ High complexity to achieve. ▪ High cost.	▪ Needs prior techniques to estimate life at design stage. ▪ Time consuming. ▪ Performed during maintenance. ▪ Inaccurate if un-calibrated. ▪ device used.	▪ Requires prior models. ▪ The factors may vary according to the nature of the research.

To calculate a component's temperature, stress and creep life, details of its material deformation, engine history and relevant fraction rule are needed. Non-Destructive Test (NDT) and Destructive Test (DT) can be used to quantify the damage further.

Post-service Approach is based on after-service sampling and examination. The state of components material can be determined by measuring or directly assessing the extent of the damage experienced. The state of components material were compared with standard scatter bands to provide a refined prediction of remaining life. Destructive and non-destructive tests and microstructural evaluation are the main methods of assessing the remaining life.

Statistical Approach is to build a relationship between the creep life and the driving factors, and to predict creep behaviour by using statistical, probabilistic and artificial intelligent methods, Francisco. et al. (2020).

Methodology

This paper focuses on creep as the major failure mode and does not discuss interactions between different failure modes. Turbomatch (Cranfield University's existing component based gas turbine performance and diagnostics software model) was used to simulate the gas turbine thermodynamic behaviour at design point and off-design point conditions. By using a physics-based model, thermal and mechanical stress analyses were performed on the HP turbine blades.

In order to study the impact of operating and ambient conditions on the creep life of a gas turbine engine's hot section, a model single shaft engine was created. In addition, the operating environment of the gas turbine engine, which plays a major role in the performance of the gas turbine and the power plant, is presented here. Daily power demand from a power plant in Zawia (a city in Libya) and profile of its ambient temperature is seen in Figure (1). It is evident from the figure that the highest power demand combined with the highest ambient temperature is around midday.

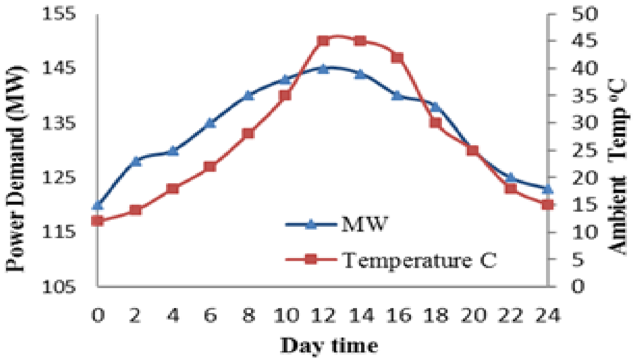

Figure (1): Ambient Temperature and Power Demand Profile for Summer Day (GECOL, 2010).

Creep Factor

To perform an impact analysis, comparison with a certain reference value is necessary. With blades creep life assessment, knowing the remnant creep life, say, 20,000 hours, is not sufficient, as it does not reflect how well the engine is being used. For example, if we state that the 20,000 hours, say, 40% shorter than expected, this would indicate that the engine has been operating under severe thermal and mechanical loading. The value of 40% in this case is an indication of the magnitude of the impact of operating the engine away from design point operation. Knowing this information allows the operators to optimise mission profiles or establish an effective maintenance plan that can reduce operation and maintenance costs.

This paper uses the Creep Factor (C_F) approach to measure the impact of actual operating conditions on creep life and to quantify how quickly the creep life is being reached relative to the specified operating condition desired by the operators. C_F is defined as the ratio between the calculated creep life remaining at the actual operating conditions and the remnant creep life calculated for the reference conditions (Abdul Ghafir et al., 2010):

$$C_F = \frac{L_c}{L_{cRef}} \qquad (1)$$

Where: L_c denotes the calculated remnant life for actual operating condition, and L_{cRef} denotes the reference remnant life at user-defined reference operating conditions.

This reference operating condition can be those of the design point, baseline operation and nominal operating conditions.

A realistic remnant life that is useful to the users will allow them to perform a realistic impact analysis, and the C_F value will help the user to assess changes in the remaining creep life of components operating at conditions, which deviate from the normal user operating conditions. The C_F will also help eliminate dependency on the OEM baseline operation which is not always achievable when the user-defined normal operating conditions are far from the suggested baseline operation (Abdul Ghafir et al., 2010). In general when:

1. $C_F = 1$, the engine is being operated at the reference condition with $Lc = Lc_{Ref}$.
2. $C_F < 1$, the engine is being operated in a worse condition than its reference condition hence reducing the blades’ remnant life.
3. $C_F > 1$, the engine is being operated under better conditions than its reference conditions thus increasing the blades’ remnant life.

Blade geOmEtry and Material Data

The component with the highest probability of requiring maintenance is the high pressure turbine (HPT) because of the effect of combined high temperature and high rotational speed on the centrifugal and thermal stresses acting on the HPT blades.

In this study, the blade geometry specifications were obtained from the industrial engine at the power plant during engine overhaul. The details of the first stage blade turbine geometry data are presented in Table (2). The material used in this investigation is Nimonic alloy (Special Metals, 2010) and its properties are shown in Table (3). Figure (2) shows an actual photograph of the blade.

Table (2): Blade Geometry.

Geometrical Parameter	Values	Unit
Tip radius	0.95	m
Root radius	0.80	m
Blade height	0.20	m
Blade chord	0.08	m
Blade mass	6.32	kg

Figure (2): Engine Blade, Courtesy of (GECOL, 2010).

Table (3): Material Data.

	Density (Kg/m^3)	Melting range °C	Specific heat (J/Kg°C)
Material	8180	1310	753

Performance Simulation

Using Turbomatch, a single-spool engine performance model was developed, based on the layout in Figure (3), and used to develop and run representative thermodynamic models of the engine investigated. The tool has the ability to simulate different thermodynamic cycles and processes while analysing the overall performance of the engine including among other things the effects of cooling flows, air and gas mixing, component degradation, variable geometry (including compressors, turbines and exhaust nozzles) as well as extraction of bleed air and shaft power off takes. Turbomatch can also calculate steady state engine performance at both design point and off-design conditions. In this study, Turbomatch was used to develop and run a thermodynamic model of the engine and the cooling flows are extracted as shown in Figure (3).

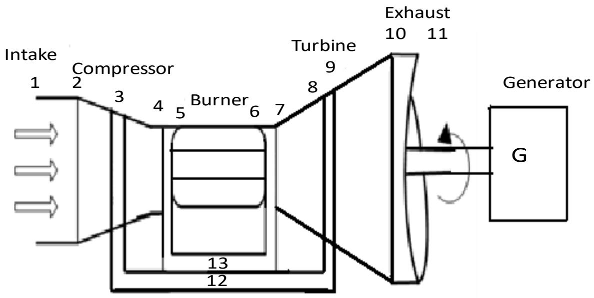

Figure (3): General Layout of the Engine.

Table (4) presents the engine performance parameters used in modelling the engine.

Table (4): Engine Performance Parameters at Design Point.

Parameter	Value
Pressure ratio	15:1
Power output	165MW
Exhaust gas flow rate	530 kg/s
Thermal efficiency	37%
Turbine entry temperature	1378 K

Thermal Model

The model is intended, primarily, to calculate the temperature of the blade for the first stage of the HP turbine. The model starts from a value of overall effectiveness calculated by the designer based on the cooling technology of the blade. The air coolant temperature (T_{cin}) entering the blades, which comes from the last stage of the HP compressor, and the temperature of gas (T_g) surrounding the blades are both determined from the Turbomatch simulation. Also, the overall cooling effectiveness is assumed based on the technology of the blade and NGV outlet temperature as shown in Figure (4) (Koff, 2003). Thus the model calculates the temperature of the blade metal (T_b). As the temperatures change with operating conditions, the model is continuously updated and the new blade metal temperature is obtained. The creep model calculates component life according to (T_b) (Torbidoni and Horlock, 2005).

$$\varepsilon = \frac{T_g - T_b}{T_g - T_{cin}} \qquad (2)$$

Re-arranging Equation (2), the blade metal temperature obtained using Equation 3:

$$T_b = T_g - \varepsilon(T_g - T_{cin}) \qquad (3)$$

Here T_g is gas stream temperature, T_b blade metal temperature, T_{cin} inlet cooling temperature and ε cooling effectiveness.

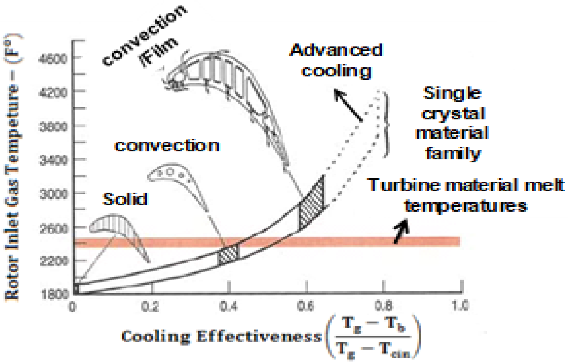

Figure (4): Cooling Mechanisms in Turbine Blades (Koff, 2003).

Blade Creep Life Assessment Model

Here, a creep life model has been developed (see Figure (5)) for use with the first stage rotor blade of a typical stationary HPT of the gas turbine. The approach used for assessing blade creep life was to develop a creep life model which consisted of sub-models for creep, thermal behaviour, stress analysis and performance using Turbomatch.

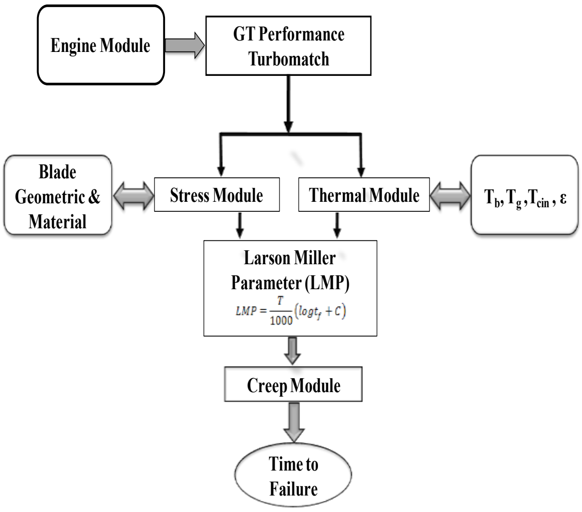

Figure (5): Creep Life Assessment Model.

The output from this model was combined with the blade geometry data to predict the stresses and temperatures in the blade metal at different locations along the span of the blade. The results from the thermal and stress model are input in the creep model (LMP) which estimates the remaining creep life of the blade.

Stress Model

While there are many different sources of stress in turbine blades, this paper considers only direct centrifugal stresses, which arise because the mass of blade and is a function of blade rotational speed (PCN).

For the creep life calculation, the centrifugal stresses on the blade were evaluated from root to tip. The data used in this model such as rotational speed was generated with Turbomatch. In this study, the blade was divided into several sections as shown in Figure (6).

It is assumed in the model that the axial velocity remains constant along the span of the blade and the centrifugal forces act at the blade section centre of gravity. The centrifugal force on a rotating section is expressed as verified by Vigna (2006):

$$\boldsymbol{CF_{sec} = \mathrm{mass} \times \omega^2 \times d_{Cg}} \quad (4)$$

Where mass is the mass of the component, ω is the angular speed of the component, d_{Cg} is the distance between the rotation axis and the section centre of gravity (Cg).

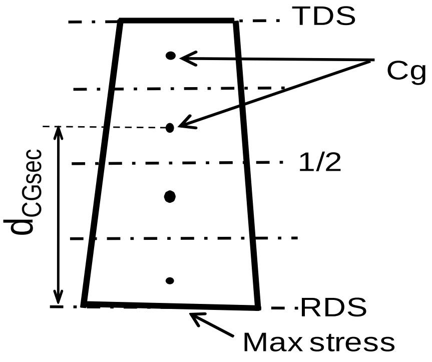

Figure (6): Typical Blade Sections.

Assuming the blade section has a rectangular shape its mass will be equal to density*cross-sectional area*height, and the centrifugal force calculated using Equation (5) will be:

$$CF_{sec} = \rho \times A_{AvCs} \times h_{sec} \times \omega^2 \times d_{Cg} \qquad (5)$$

Where ρ is the density of the material, A_{AvCs} is the average cross-sectional area between the top and the bottom of the section, h_{sec} is the section height, and d_{Cg} is the distance between the rotation axis and the section Cg. Thus the centrifugal stress acting on a blade of constant cross-sectional area can be calculated using Equation (6):

$$\sigma_{Sec} = \rho \times h_{sec} \times \omega^2 \times d_{Cg} \qquad (6)$$

Creep Model

To obtain a reasonably conservative estimate of creep life, either at the current operating condition or the reference operating condition, the LMP approach was used in the model.

From Arrhenius's Law, the equation can be expressed as (Haslam and Cookson, 2007) :

$$LMP = \frac{T}{1000}(\log t_f + C) \qquad (7)$$

Re-arranging, t_f can be written as:

$$t_{f=} 10^{\left(\frac{1000\,LMP}{T} - C\right)} \qquad (8)$$

Where LMP is the Larson-Miller Parameter, T is the temperature of the material, t_f is the time to failure, and C is a constant. The constant C is often generalised to 20 in industrial applications but it can vary between 13 and 27 depend on material in equation Kaufman et al. (2007).

For a turbine blade of a known specific material, where the metal temperature and stresses have been found from previous models, t_f for both current and reference operating conditions was estimated before the C_F was determined from Equation (1). The stress will vary with blade section, so creep life will also be different for different blade sections. The minimum creep life calculated will be taken as the value which represents the blade’s remnant life.

Industrial GT Performance Deterioration

The deterioration of industrial gas turbine has been studied since the ideal cycle of Brayton was modified to represent the real conditions. At the end of 1940’s it was observed that the gas turbine deterioration affected the power production and increased the fuel consumption Zwebek and Pilidis (2003a); Zwebek and Pilidis, (2003b). There are several types of deterioration that might occur in a gas turbine engine, and this study considered compressor deterioration due to the ingestion of dust mixed with the air otherwise referred to as fouling, which decreases the compressor isentropic efficiency as well as flow capacity. Fouling and erosion have been demonstrated to affect the thermal efficiency and output power of the engine Ben Hariz (2010). Moreover, the accumulation of dust reduces the tip clearance and increase the surface roughness of blades Kurz and Brun (2001). These changes in the blades affect the compressor delivery pressure. In this study, a clean and deteriorated engine with up to 5% reduction of efficiency and flow capacity are considered.

Results and Discussion

In this section, parametric analysis of the effect of turbine entry temperature (TET), ambient temperature and power demand are presented. During this investigation, the reference off-design point was selected for relative rotational speed (PCN), and cooling effectiveness (ε) of 0.98 and 0.55 respectively. A PCN value of 0.98 means a rotational speed that is 98% of absolute design rotational speed. Stress and creep life distribution along the blade span at various operating conditions are shown in Figures (7)-(13). Figure (7) shows the stresses distribution along the span of the blade, showing the maximum stress occurring at the root of the blade. Since the stress distribution is effected by PCN alone, the σ_{sec} stress was not affected by temperature.

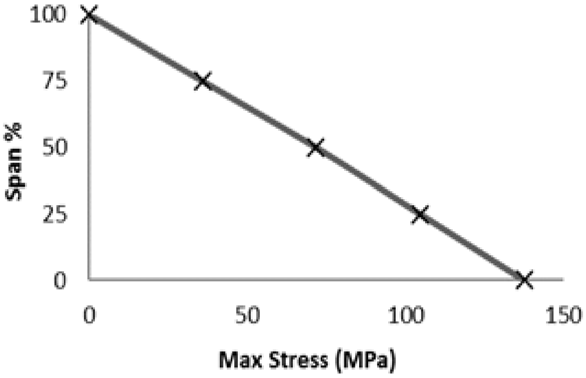

Figure 7: Maximum Stress Distribution along the Blade Height.

Effect of Ambient Temperature on Creep Life

Figure (8) shows the effect of ambient temperature on HP blade creep life. The design reference point was taken as (TET=1378 K, T_a= 288.15 K) equivalent to Creep Factor = 1. It must be noted that the graph depicts a scenario where there is a constant power demand with increasing ambient temperature and consequent increase in firing temperature. As would be expected, a decrease in ambient temperature from its reference value of 0 °C to -5°C results in an improved Creep Factor, from 1.0 to 1.3 (see Figure (8)). This is due to the fact that at lower ambient temperature, compressor delivery temperature is lower, resulting in a reduced fuel flow requirement and thus a reduction in firing temperature, as well as improved cooling capability since the inlet cooling temperature is brought down (see Equation (3)). Therefore, a reduction in Creep Factors is expected at higher ambient temperature. For that reason, it can be seen that the Creep Factor dropped almost linearly from its reference value to 0.22 when the ambient temperature is increased to 30°C. Further increase in the ambient temperature will definitely see further reduction in the blade's creep life.

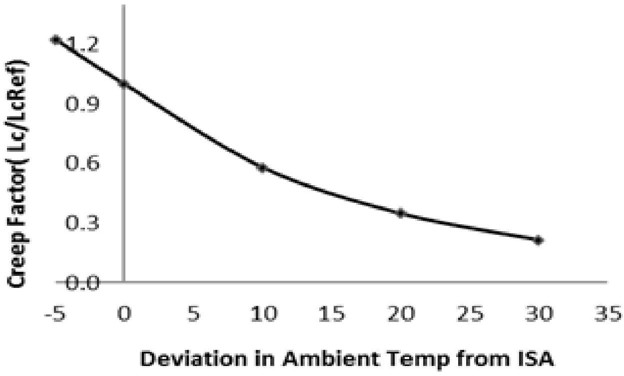

Figure (8): Blade Creep Life at Different Ambient Temperature.

Effects of TET AND Power Demand on Creep LIFE

It is important to note that for both cases, the engine TET was chosen as a handle. The effect of changes in TET was investigated from 1280 K to 1400 K in steps of 20 K. The reason for choosing this range is to show the effect on the blade's creep life of having high and lower TET value relative to its design point which is 1378 K. Furthermore, an ambient temperature of 288.15 K, and ε = 0.55 were taken as reference values in this investigation. The increase in the Creep Factor indicates an increase in the blade's creep life.

The variation of Creep Factor at various TET values and power settings has the detrimental effect of higher operating temperature for the clean engine, as can be seen in Figure (9). The Creep Factor is less than 1.0 when the TET was 1400K and increases to approximately 2.0 at 1340 K. A similar effect can be seen with the power demand variation. The reduction in TET from 1400 K to 1340 K will consequently reduce the power. Figure (9) shows that as the shaft power reduces, the blades creep life will increase due to similar reasons as discussed earlier. It is also shown in Figure (9) that by increasing power from 140 MW to 165 MW, with the associated increase in TET, the Creep Factor drops by 75%.

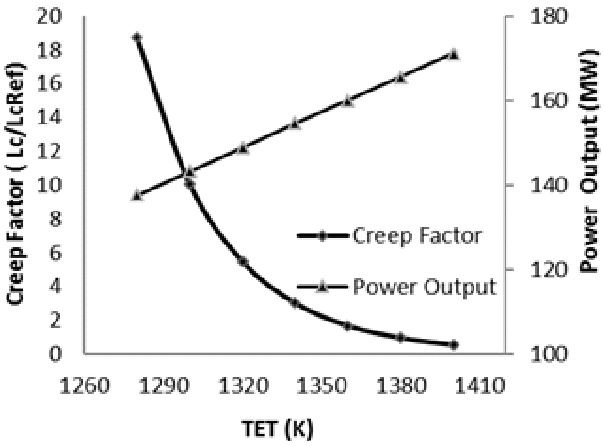

Figure (9): Blade Creep Life with Different TET and Power Demand for Clean Engine.

Figure (10) shows that a lower ambient temperature results in lower blade metal temperature. The drop in metal temperature will increase the blade's remaining life (see Figure (8)). In Figure (10) it can also be seen that the stress does not contribute to a significant change in the blade's remaining life. This can be seen clearly as the maximum stress depicted in the figure remained unchanged during the investigation. This was because the centrifugal stress is a function of PCN which remained constant at 98% during this investigation.

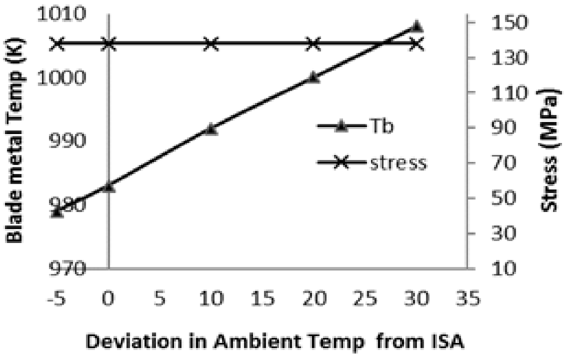

Figure (10): Dev. Ambient Temperature Against Blade Metal Temperature and Stress.

Effect of Compressor Degradation on Creep Life

Degradation in engine components, particularly the compressor, effects engine life. Degradation in engine compressor (implemented here as equal levels of loss in compressor efficiency and flow capacity) results in higher compressor delivery temperature, as it is shown in Figure (11). An increase in compressor delivery means that cooling air would be delivered to the turbine blade at a higher temperature for the degraded case. This would be reflected in a higher blade metal temperature as shown in Figure (12).

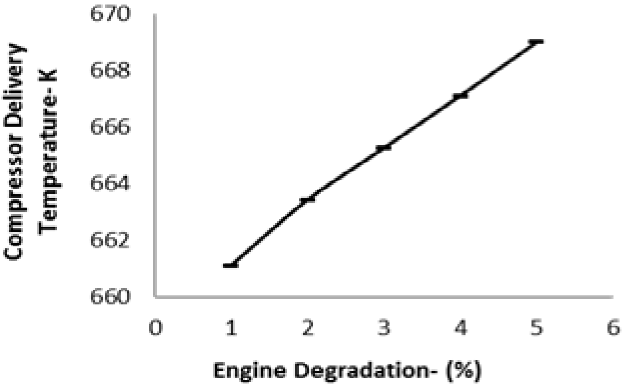

Figure (11): Engine Degradation with Compressor Delivery Temperature.

The impact of engine degradation on blade metal temperature is shown in Figure (12). In this case, the firing temperature is maintained the same. A 5 K increase in blade metal temperature resulted in 20% reduction in Creep Factor. The change in the metal temperature as shown in Figure (12) did not change so much (from 1024 K to 1029 K) since for these case studies TET was kept constant. Nevertheless the small changes are due to the changes in the compressor delivery temperatures (see Figure (11)) as degradation increases. The increase in the compressor delivery temperature is reflected as an increase in the coolant inlet temperature. This reduces the air cooling capability which consequently increases the blade metal temperature as shown in Figure (12).

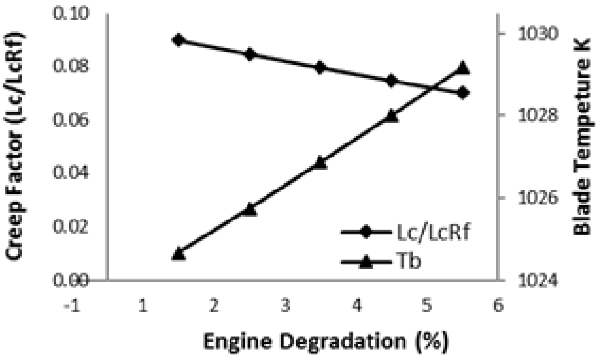

Figure (12): Blade Creep Life and Metal Temperature at Different Engine Degradation Levels (T_a= 318 K).

Figure (13) shows that, the degraded engine's temperature has to be increased by 111 K (1489 K – 1378 K) above that of the clean engine to give the design point power output, substantially reducing the useful life of the engine. In other words, engine degradation results in a reduction in power output; therefore, if the engine is already being operated close to its base load, then for the degraded engine to meet the power demand, it has to be operated at higher TET. This case is illustrated also in Figure (13).

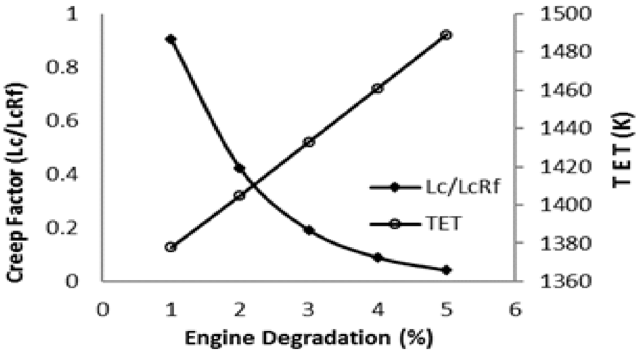

Figure (13): Blade Creep Life and TET with Engine Degradation.

It is clear that over-firing of the engine reduces the life of the hot section component significantly and should be avoided if possible. Effective maintenance schemes or use of other engines with spare capacity is recommended in order to meet the required power demand.

Conclusions

This paper has presented effects of design parameters and operating conditions on the HP turbine blade creep life. Clean and deteriorated engines were considered. In addition, the paper highlights how different operating conditions and design parameters can influence the blade's creep life.

A thermodynamic performance model of a stationary gas turbine engine was developed to simulate both design and off-design conditions. The first stage turbine blade was measured in order to facilitate the estimation of creep life. Then the stress and temperature along the span of the blade was calculated to obtain the blade's remnant creep life.

With the material investigated, it was found that increasing the TET decreases the blade creep life along the span of the blade.

Blade metal temperature and ambient temperature have a strong influence on blade creep life, and these two factors will mainly determine the section of the blade with the lowest creep life. Emphasis should be given to the level of temperature and stress, and the locations of maxima along the blade, to better identify the location of minimum creep life. A deeper understanding of the relationship between operating conditions and design parameters will allow designers and users to obtain better trade-offs between different design options and maintenance decisions.

This analysis has strong economic implications because an understanding of creep life can lead to specialised maintenance in order to prolong the life of the hot gas path components. Depending on the way the engine is operated the maintenance costs will vary and the time before major overhaul will also be affected. Estimates of creep life can be used to avoid unplanned shut downs and loss of production.

Nomenclature

A_{AnSec}	Blade section annulus area	T_a	Ambient temperature
A_{CS}	Blade section cross-section area	T_b	Blade metal section temperature
T_{Cin}	Inlet coolant temperature	TET	Turbine entry temperature
T_g	Section gas temperature	C	Parameter constant=20
d_{CG}	Distance between the rotation axis and the section Cg	LMP	Larson-Miller parameter
d_{CGsec}	Distance between the section Cg to the respective section	ε	Cooling effectiveness

t_f	Time to failure	ρ	Blade density
σ_{CFSec}	Centrifugal stress at each blade section	ω	Angular speed
CDP	Compressor delivery pressure	OEM	Original equipment manufacturer
C_F	Creep factor	MW	Mega watt
CF_{sec}	Section's centrifugal forces	DT	Destructive test
Cg	Centre of gravity	L_c	Calculated remnant life
DT	Destructive test	L_{cRef}	Reference remnant life
G	Generator	Kg	Kilo Gramm
GECOL	General Electrical Company of Libya	s	second
GT	Gas turbine	k	Kelvin
H	Height	J	Joule
HPT	High pressure turbine	°C	Celsius
NDT	Non-destructive test	m	Meter
RTDF	Radial temperature distortion factor	T	Temperature
ISA	International Standard Atmosphere		

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